The sky distribution of UHECRs: clues to their origin

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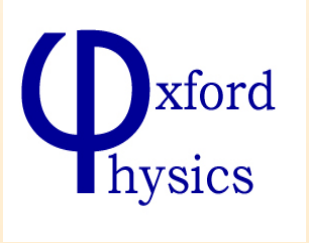


COSMO 02. Chicago, 19 September 2002.

Outline

1. Large angular scale structure of UHECR data.

   - Dubosky & Tynakov, JETP 68 (1999) 107.
   - Medina Tanco & Watson, Astropart. Phys. 12 (1999) 25.
   - Evans, Ferrer & Sarkar, Astropart. Phys. 17 (2002) 319.

2. Small-scale clustering.

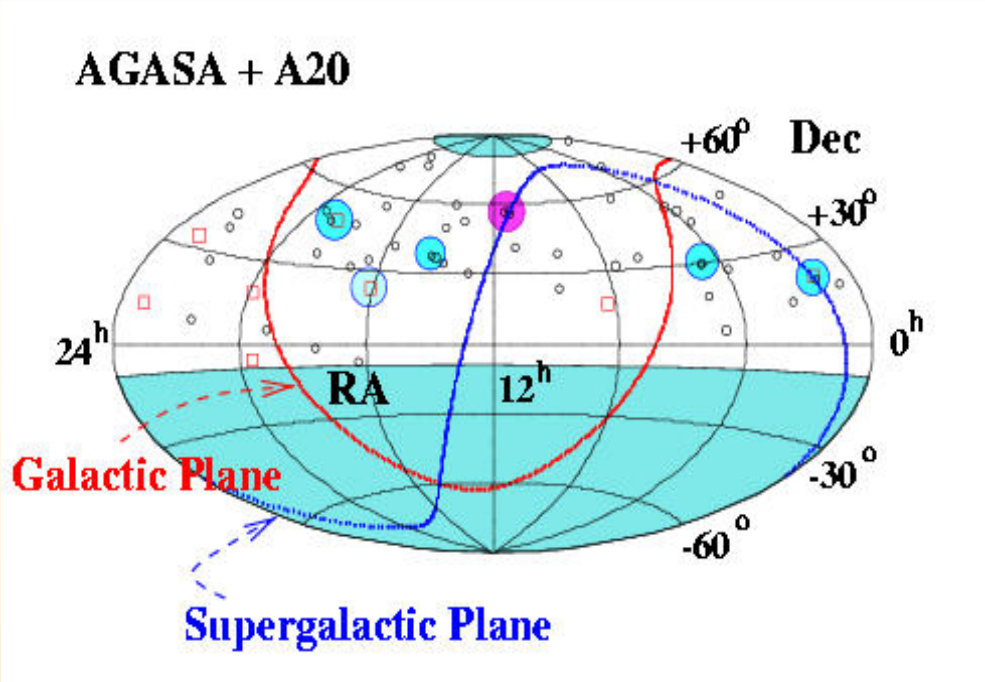
   - Uchihori et. al., Astropart. Phys. 13 (2000) 151.
   - Tinyakov & Tkachev, PRL 85 (2000) 1154 & JETP 74 (2001) 3.
   - Blasi & Sheth, PLB 485 (2000) 233.
   - Evans, Ferrer & Sarkar, work in progress.

3. Correlation with astrophysical sources?

   - Tinyakov & Tkachev, JETP 74 (2001) 445.
   - Evans, Ferrer & Sarkar, work in progress.

4. Conclusions.

UHECR observations



- Roughly 100 UHECR events above $4\ 10^{19} eV$ have been recorded. Protons or nuclei causing them must originate within the Local SuperCluster (≤ 100Mpc).

- Searches for nearby astrophysical sites have failed so far.

- Slow decays of particles with $m \geq 10^{12} GeV$ constituting (part of) the DM in our galactic halo could produce UHECRs.

Constrains from the angular distribution

- Data structure at large angles is described as being broadly isotropic. Have to take into account intrinsic anisotropy of the detector's response.

- DM in our halo would produce a dipole anisotropy caused by the offset of the Sun from the Galactic Center.

- Compare to the signal caused by rich clusters in case UHECRs track local galaxy distribution.

- The AGASA experiment has detected several doublets and triplets of events within the angular resolution of the experiment.

- This clustering is difficult to explain if CRs hit isotropically the Earth's atmosphere. Flux variations, produced by e.g. clumps of DM or point sources, are required.

- Other experiments like HP, Yakutsk, ... do not appreciate a statistically significant effect above $4\,10^{19} eV$.

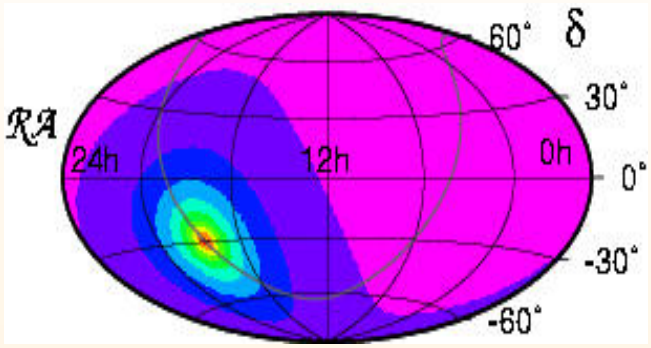
Structure at large angles

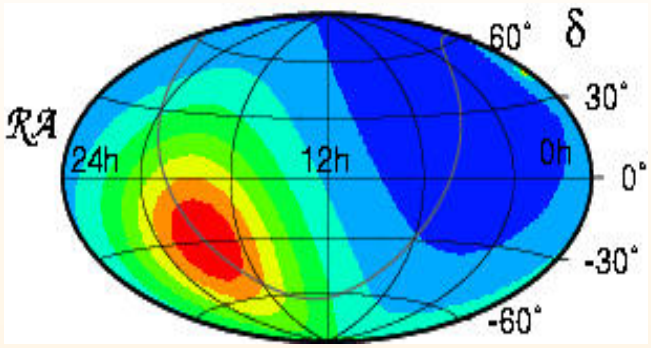
Detectors run with efficiency allow use of amplitude & phase of the 1st. harmonic to quantify the anisotropy in right ascension that can be compared with the predictions for halo distributed DM and different astrophysical catalogues.

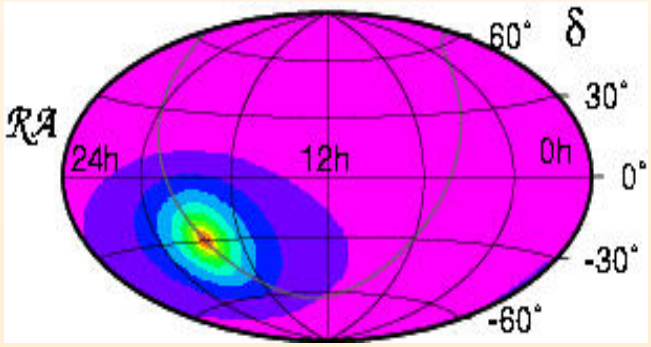
As the profile of the Galactic Halo is poorly known, I will consider different choices: cusped NFW (N-body simulations) and isothermal (central part not dominated by DM).

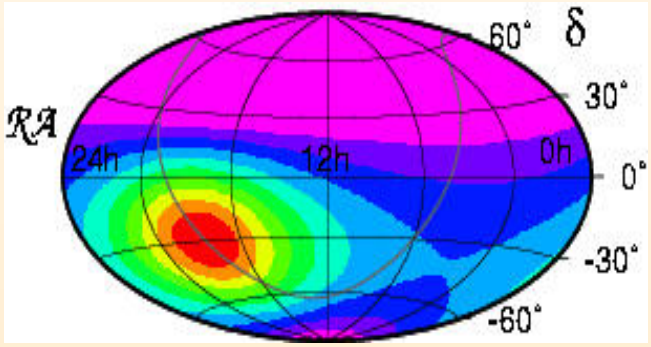
I will also entertain the idea that super-massive BH's in (not necessarily active) galactic nuclei cause UHECRs, taking four samples from the RC3 catalogue: normal (M32) and bright (Cen A) galaxies and closer than 50 or 100 Mpc.

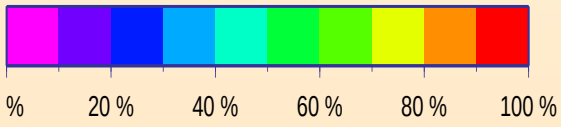
UHECRs from decaying DM.



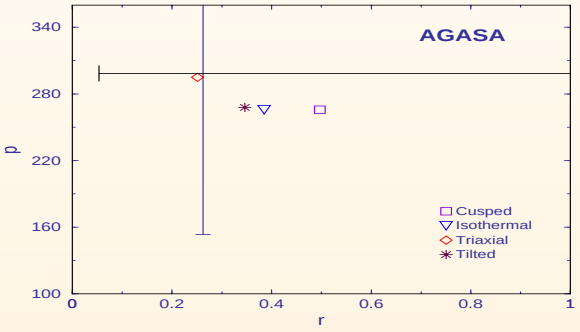


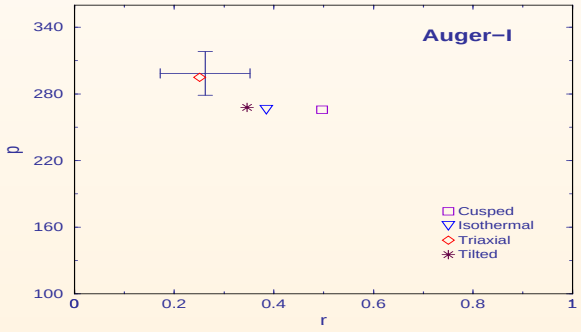


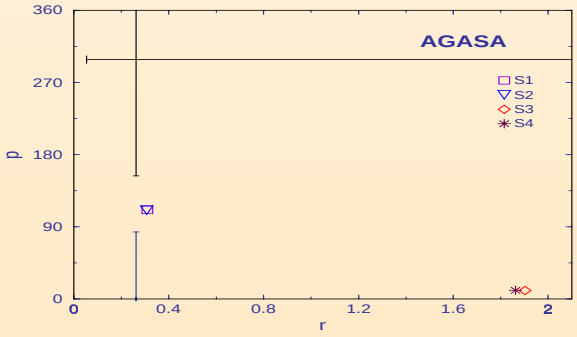


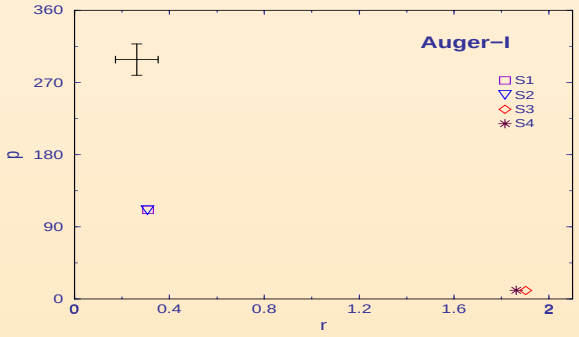


Harmonic analysis









Harmonic analysis

- Amplitude expected: $\mathcal{S} \leq 0.4$ (higher for cusped halo). Controlled by core radius of the halo (could be directly measured). Phase points towards GC except for triaxial halo. The shape of the halo affects the phase.

- Higher signal expected for South Auger. Probabilities above 35% for all models. Will decrease to $\sim 1\%$ with Auger statistics.

- Samples I & II, containing almost all the nearby galaxies yield amplitudes comparable to the decaying DM hypothesis whereas III & IV give rise to a too large an anisotropy to fit present AGASA & HP data.

- Phase is crucial to distinguish from decaying DM. It is largely controlled by the Virgo (North) and Fornax (South) clusters. Need 350 (500) events at South Auger to measure phase direction.

- Typically 350 events will be enough for South Auger to distinguish between both origins. This can be obtained within the first three years of operation.

Small-scale clustering

AGASA collaboration reports 5 doublets and 1 triplet within 2.5^o above $4\times10^{19}eV$ (58) events. (Although only one doublet is observed in HP and no clusters are observed in Yakutsk and VR data).

The probability for an isotropic distribution to produce this configuration is below 0.1%. Clustering is accounted for by variations in the incoming flux of UHECRs.

Such flux variations could be produced by a small number of point-like sources or by clumps in the halo of DM.

The statistical tool used at small angles is the two-point correlation function:

$$\mathcal{N}(\theta) = \frac{1}{2S(\theta)}\Sigma_{i\neq j}R_{ij}(\theta)$$

DM clumps in the galactic halo

Numerical N-body simulations of structure formation show that 10% of the DM halo should be in the form of small clumps.

The mass distribution of these clumps follows a $1/m^2$ law between $10^7 M_\odot$ and $10^{10} M_\odot$.

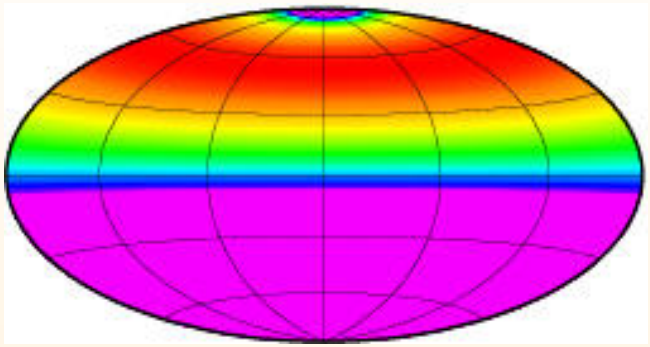
The density profile of the clumps is fairly unknown but simulations converge to a NFW profile for halo sizes ranging from clusters to galaxies.

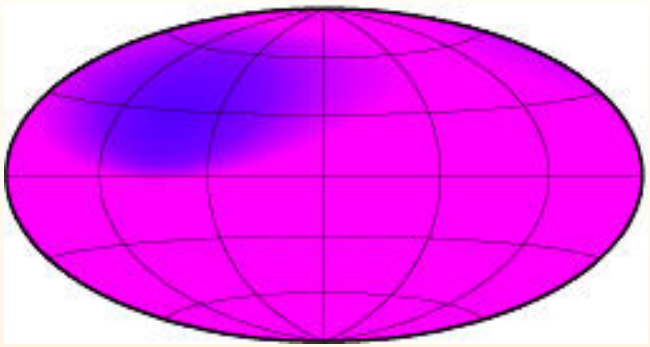
The spatial distribution of clumps shows *anti-bias* with respect to the smooth background profile. Clumps tend to be scarce near the galactic center due to merging.

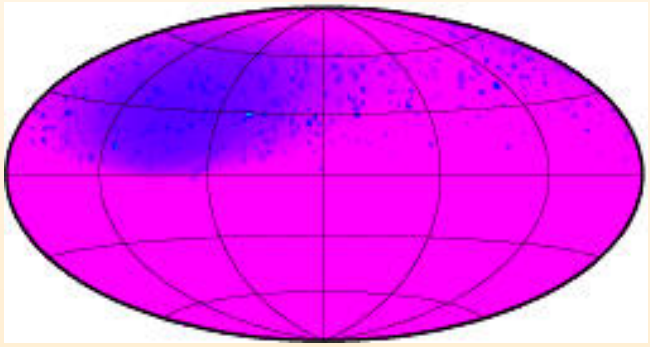
Previous studies of clustering in DM models have shown that the required amount of doublets can be accommodated but they have considered SIS type clumps and report that half of the doublets comes from the underlying NFW halo.

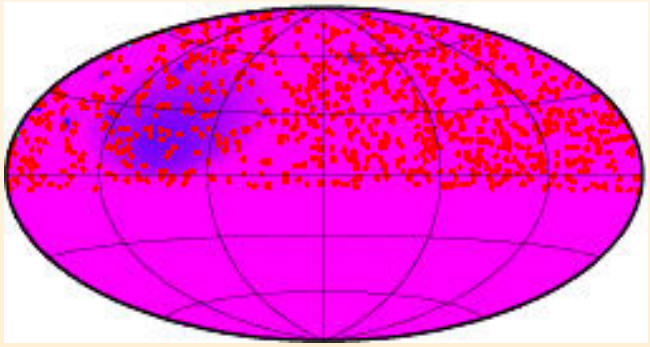
Both NFW and SIS profiles should be regulated at the origin when computing the expected UHECR flux from decaying DM.

UHECRs from a clumpy halo: AGASA view

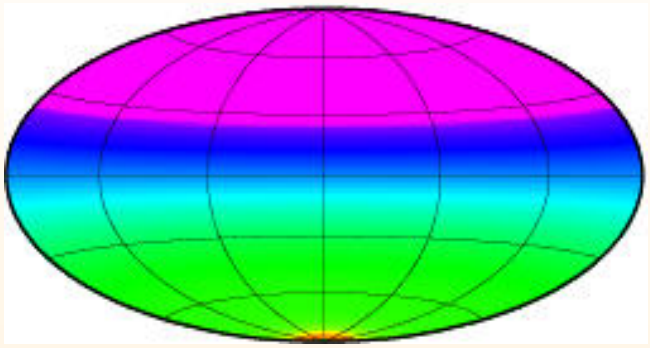


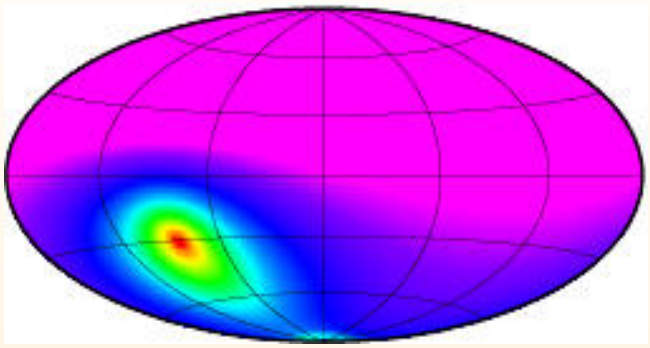


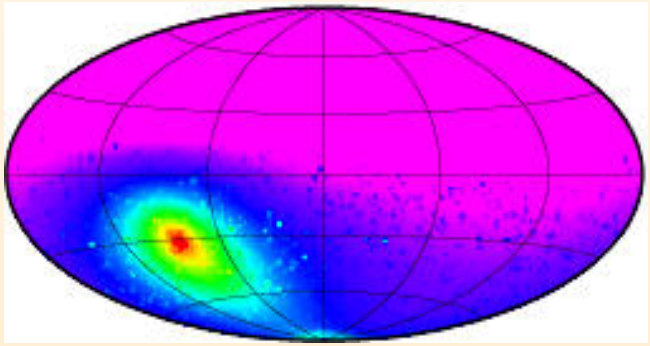


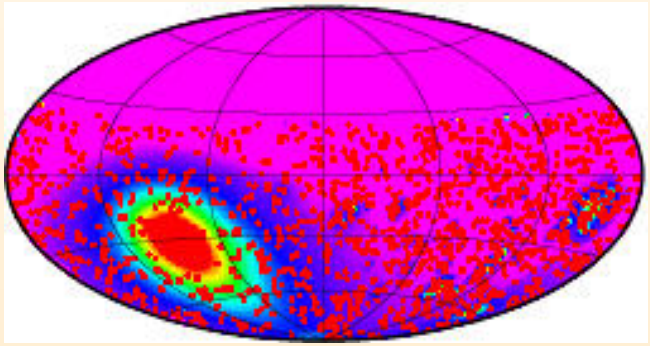


UHECRs from a clumpy halo: Auger view

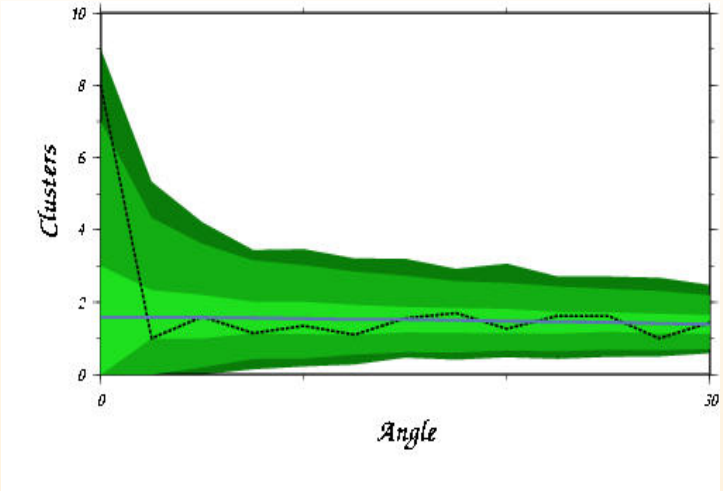


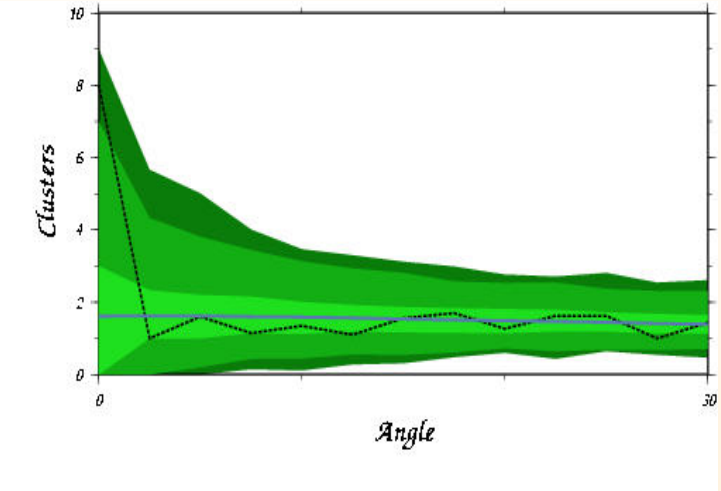


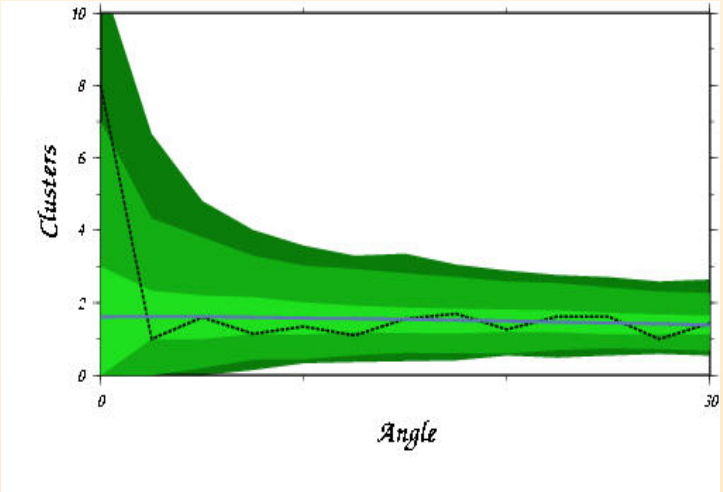


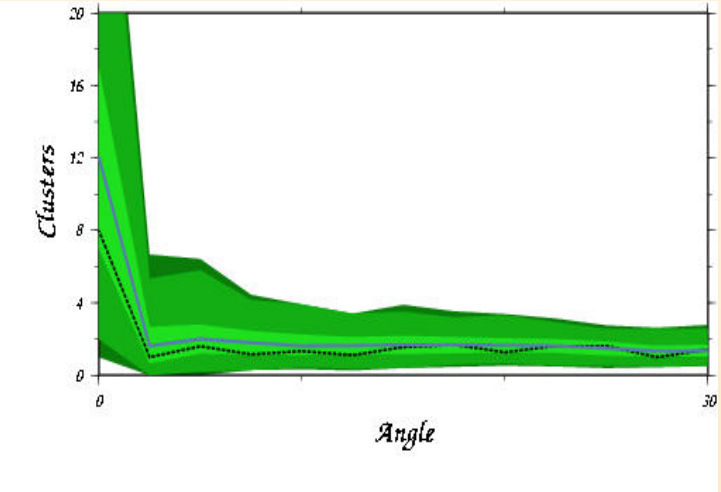


Two-point correlation function

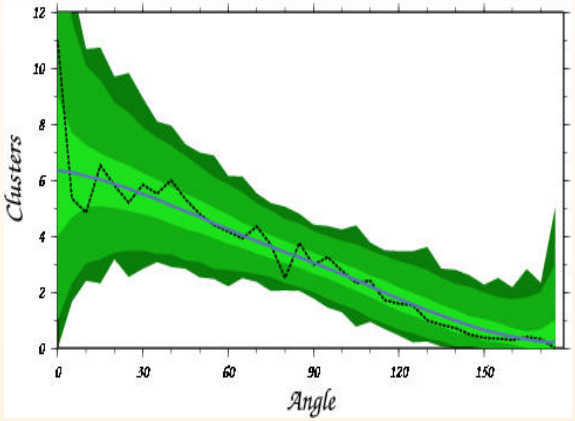


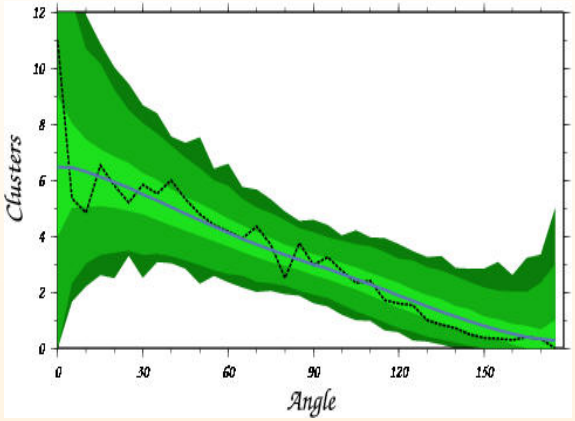


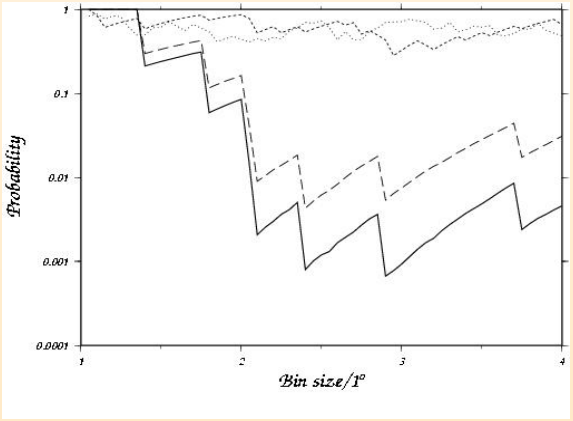




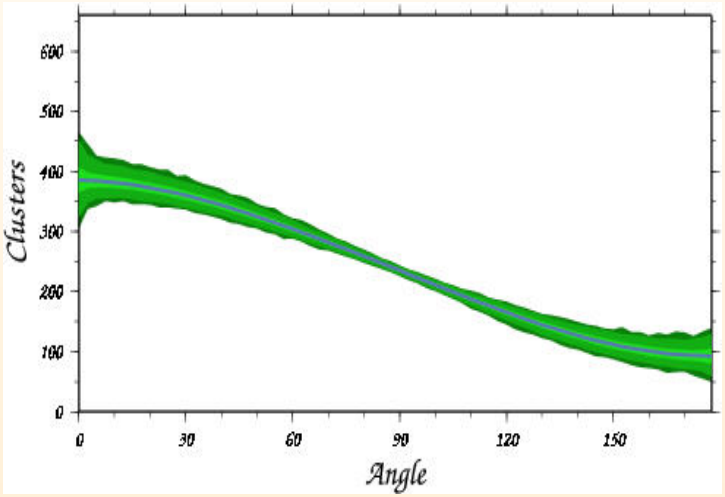
Bin size dependence

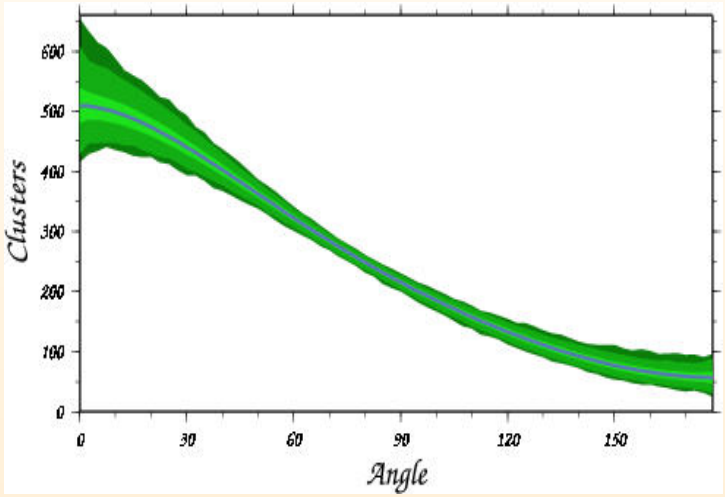






Auger predictions

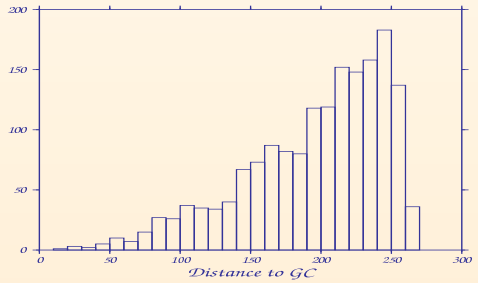


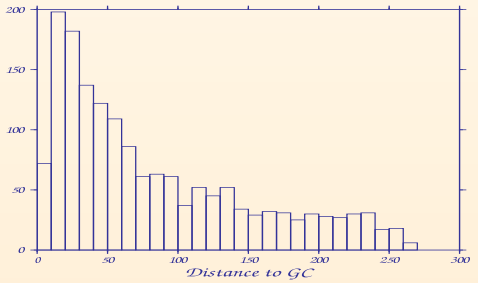


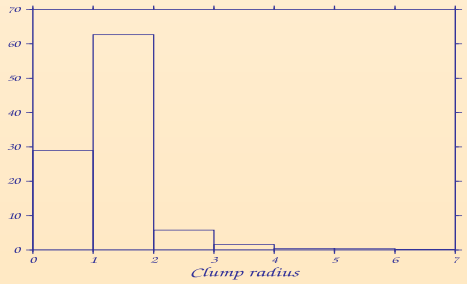
NFW versus SIS clumps

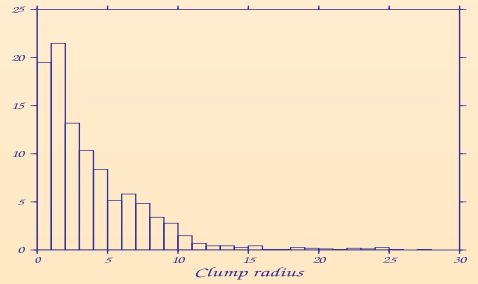
SIS type clumps are very sensitive to the core radius.

Also different size and spatial distribution of considered populations explain the variation in the clustering prediction.





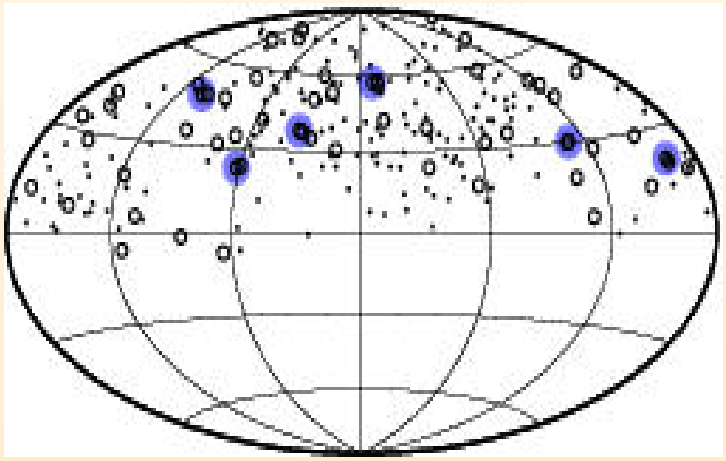


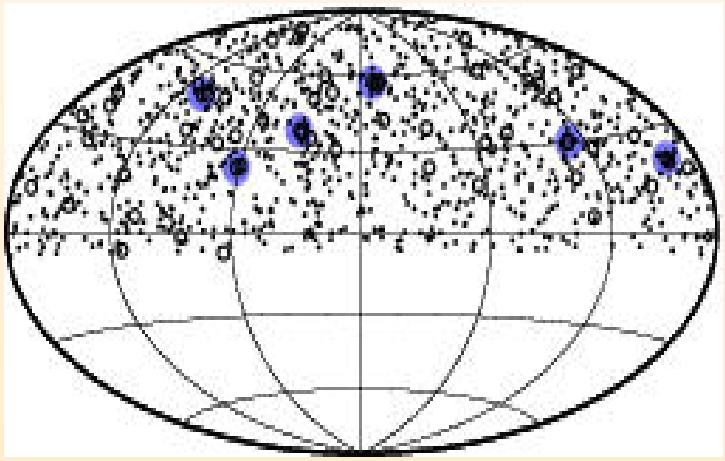


Correlation with astrophysical sources

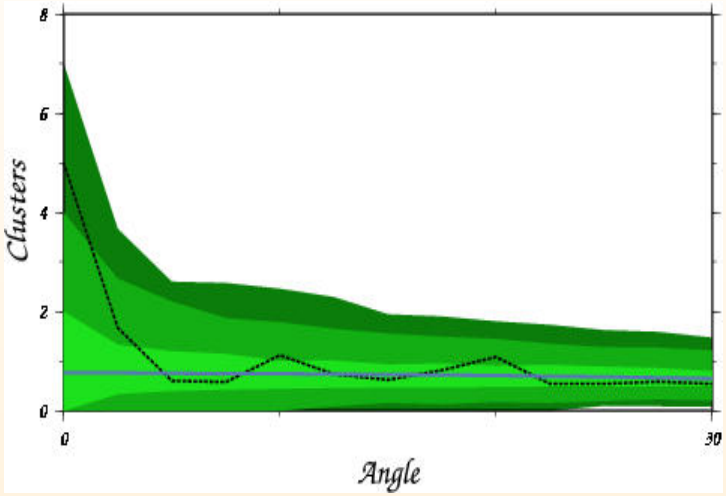
The correlation function has been used to claim that UHECRs come from a selected population of BL lacs.

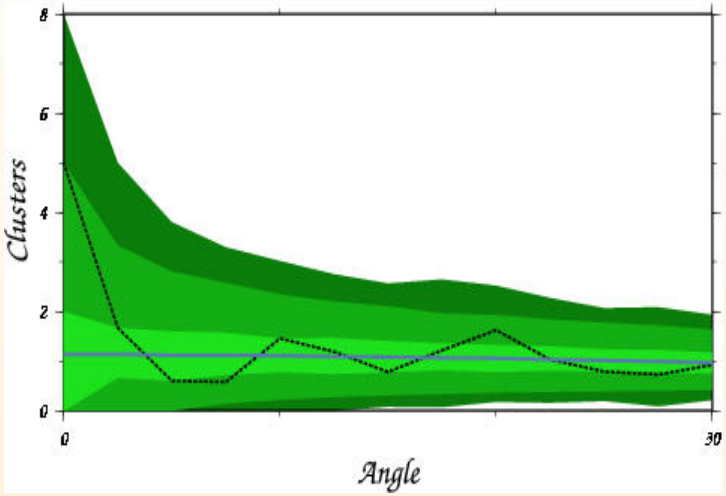
The study combines AGASA data above $4.8 \times 10^{19} eV$ with Yakutsk data above $2.4 \times 10^{19} eV$ and selects BL lacs according to arguable criteria (e.g. only BLs beyond $z = 0.1$ are considered). Will try to relax this cuts to see if the correlation signal is robust and compare it with the correlation expected for GRBs.

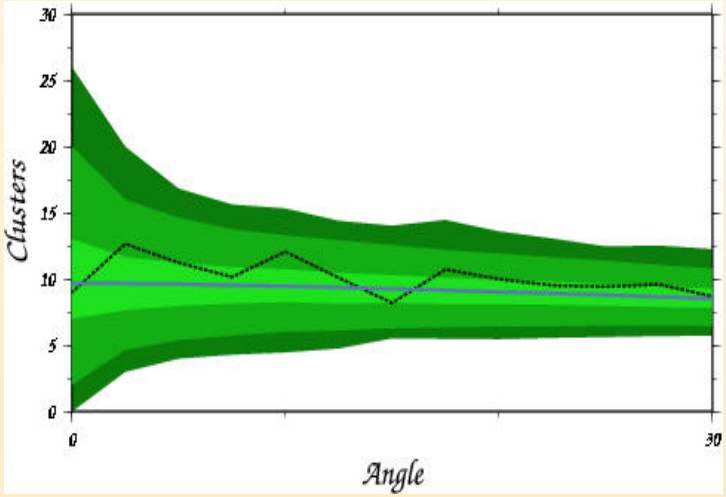


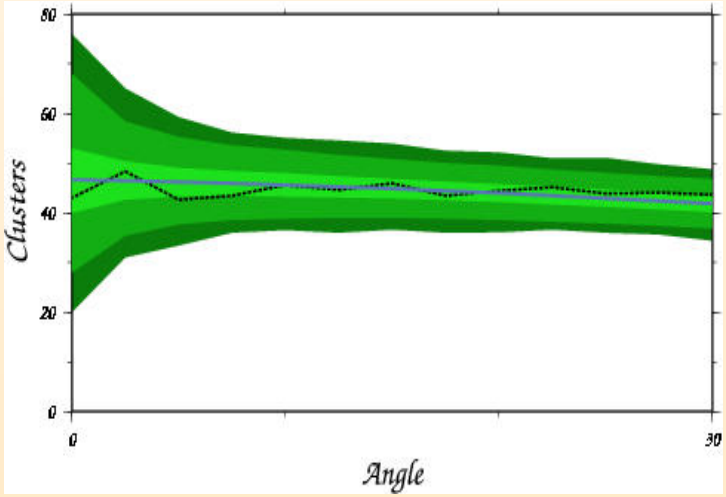


Correlation function









Conclusions

- Theories of the origin of the UHECRs produce characteristic angular signatures in the sky that can be used to constrain them. Larger data sets that will be available in the future will enhance this tool.

- The wide angular distribution of the present data, usually described as isotropic, can accommodate fairly anisotropic models like the dipole towards the galactic center predicted by Super-heavy DM. Pierre Auger experiment will be able to disentangle different models.

- Small angular clustering seen by AGASA is difficult to explain by isotropic models. Other datasets do not show clustering at a significant level.

- Super-heavy DM clumps in the galactic halo do not predict clustering unless very singular profiles for the clumps are considered.

- Correlation with BL lacs is not significant when cuts in the data and source catalogues are removed.